

LETTER TO THE EDITOR

# Tuning in on Cepheids: Radial velocity amplitude modulations <sup>★</sup>

## A source of systematic uncertainty for Baade-Wesselink distances

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### ABSTRACT

**Context.** Classical Cepheids are crucial calibrators of the extragalactic distance scale. The Baade-Wesselink technique can be used to calibrate Cepheid distances using Cepheids in the Galaxy and the Magellanic Clouds.

**Aims.** I report the discovery of modulations in radial velocity (RV) curves of four Galactic classical Cepheids and investigate their impact as a systematic uncertainty for Baade-Wesselink distances.

**Methods.** Highly precise Doppler measurements were obtained using the *Coralie* high-resolution spectrograph since 2011. Particular care was taken to sample all phase points in order to very accurately trace the RV curve during multiple epochs and to search for differences in linear radius variations derived from observations obtained at different epochs. Different timescales are sampled, ranging from cycle-to-cycle to months and years.

**Results.** The unprecedented combination of excellent phase coverage obtained during multiple epochs and high precision enabled the discovery of significant modulation in the RV curves of the short-period *s*-Cepheids QZ Normae and V335 Puppis, as well as the long-period fundamental mode Cepheids  $\ell$  Carinae and RS Puppis. The modulations manifest as shape and amplitude variations that vary smoothly on timescales of years for short-period Cepheids and from one pulsation cycle to the next in the long-period Cepheids. The order of magnitude of the effect ranges from several hundred  $\text{m s}^{-1}$  to a few  $\text{km s}^{-1}$ . The resulting difference among linear radius variations derived using data from different epochs can lead to systematic errors of up to 15% for Baade-Wesselink-type distances, if the employed angular and linear radius variations are not determined contemporaneously.

**Conclusions.** The different nature of the Cepheids exhibiting modulation in their RV curves suggests that this phenomenon is common. The observational baseline is not yet sufficient to conclude whether these modulations are periodic. To ensure the accuracy of Baade-Wesselink distances, angular and linear radius variations should always be determined contemporaneously.

**Key words.** Methods: observational – Techniques: radial velocities – Stars: variables: Cepheids – Stars: distances – distance scale – Stars: individual: QZ Nor, V335 Pup,  $\ell$  Car, RS Pup

## 1. Introduction

Classical Cepheids are crucial distance tracers over the range from several hundred parsecs up to one hundred Megaparsec. Thanks to this, Cepheids and type Ia supernovae together allow a one-step calibration of the Hubble constant,  $H_0$  (e.g., Riess et al. 2011; Freedman et al. 2012). Such extragalactic distances are estimated using the Cepheid period-luminosity relation (PLR), which was originally discovered by Henrietta Leavitt (Leavitt 1908; Leavitt & Pickering 1912). The calibration of this relationship is very important for astronomy, the distance scale, and cosmology, since about half of the methods promising percent precision on a calibration of  $H_0$  are Cepheid-related (Freedman 2013).

Accurate Cepheid distances are required to achieve an accurate calibration of the PLR. This endeavor has a rich history and much literature can be found on the subject (see Feast 1999). For the Galactic PLR calibration, there are essentially

three methods that can provide good distance estimates. The gold standard among these are trigonometric parallaxes; see notably Feast & Catchpole (1997) and van Leeuwen et al. (2007), who used the parallaxes measured by the *Hipparcos* space mission. Benedict et al. (2002, 2007) employed the *Hubble Space Telescope* to measure highly precise parallaxes of ten Cepheids. Within the next two to eight years, the recently launched space mission *Gaia* will provide Cepheid parallaxes of unprecedented accuracy (tens of  $\mu\text{arcsec}$ ), and the program by Riess et al. (2014) holds great promise to determine parallaxes of Cepheids within 5 kpc with similar accuracy.

Another important means of calibrating the PLR is using Cepheids associated with open clusters; for example, see Turner & Burke (2002), Turner (2010), and Anderson et al. (2013). In this case, host cluster distances provide independent distance estimates for member Cepheids.

Finally, Cepheid distances can be determined by exploiting the pulsations via different variants of the Baade-Wesselink (BW) technique (Baade 1926; Becker 1940; Wesselink 1946). In this way, precise distances to many ( $>100$ ) Cepheids in the Galaxy and the Magellanic Clouds have been determined (Gieren et al. 1993, 1998; Storm et al. 2004, 2011; Fouqué et al. 2007; Groenewegen 2008, 2013). Recently, the infrared ver-

<sup>★</sup> Based on observations collected at ESO La Silla Observatory using the *Coralie* spectrograph mounted to the Swiss 1.2m Euler telescope. The derived radial velocities are available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or at <http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/>

sion of the surface brightness technique (Thompson 1975; Barnes & Evans 1976) has become the most successful in terms of precision, since it is calibrated using interferometric measurements of red giant stars and supergiants (Fouqué & Gieren 1997), as well as classical Cepheids (Kervella et al. 2004b). Using the VLTI, Kervella et al. (2004a) were able to interferometrically measure angular variations due to pulsation and achieved a PLR calibration based on eight Galactic Cepheids.

BW distances are determined by measuring angular (e.g., via interferometry, or optical & near-IR photometry) and linear (via Doppler measurements) radius variations. Following Kervella et al. (2001) the distance is computed as follows:

$$d[\text{pc}] = 9.305 \cdot \frac{2\Delta R}{\Delta\Theta}, \quad (1)$$

where  $\Delta R [R_\odot]$  denotes the linear radius variation, and  $\Delta\Theta [\text{mas}]$  is the variation in angular diameter.

It is well known that both  $\Delta\Theta$  and  $\Delta R$  should be measured during the same pulsation cycle. In practice, however, this is not always possible owing to telescope time restrictions, especially when working with interferometry or statistical data sets that should yield the most precise PLR calibrations. Furthermore, Cepheid pulsations are usually considered to be rather regular (apart from well-known period changes and a few peculiar cases, such as HR 7308 (Burki et al. 1982) or Polaris, cf. Turner 2009 and references therein). For instance, Taylor et al. (1997) found no indication of cycle-to-cycle variations in radial velocity (RV) curves at the level of  $600 \text{ m s}^{-1}$  in  $\ell$  Car, and Marengo et al. (2004) conclude that such an effect is negligible compared to other sources of systematic uncertainty. The present work, however, demonstrates that significant RV modulations can be found in some Cepheids not usually considered to be peculiar.

Modulation can lead to systematic errors in Baade-Wesselink distance estimates if  $\Delta\Theta$  and  $\Delta R$  in Eq. 1 are determined using data from different pulsation cycles. Consider that  $\Delta R$  is computed using a projection factor,  $p$ , as

$$\Delta R = p \cdot \int v_r dt. \quad (2)$$

Assuming  $p$  does not vary between pulsation cycles, modulation will result in different  $\Delta R$  determined from data observed at different epochs. We furthermore assume that  $\Delta\Theta$  is also subject to modulations (i.e., they relate to the photospheric radius) and is determined during epoch 1, then we can quantify the relative distance error resulting from using  $\Delta R$  measured during epoch 2 instead of epoch 1 as

$$\text{err}(d) \equiv \frac{d_1 - d_2}{d_1} = \frac{\Delta R_1 - \Delta R_2}{\Delta R_1} = \frac{\int_1 v_r - \int_2 v_r}{\int_1 v_r}. \quad (3)$$

This error is independent of the value of  $p$ . In the following, the integral is referred to by its equivalent,  $\Delta R/p$ .

In this *letter*, I report on newly-discovered RV modulations and estimate the systematic error that results from employing non-contemporaneous  $\Delta R$  and  $\Delta\Theta$  according to the above reasoning. Following an overview of the observational setup in Sect. 2, RV modulations and systematic BW distance error estimates are presented in Sect. 3. Section 4 discusses possible origins of this phenomenon, and Sect. 5 provides brief conclusions. Supporting figures are provided in the online appendix.

## 2. Observations

The radial velocities presented here were determined from observations taken between April 2011 and February 2014 using the fiber-fed high-resolution ( $R \sim 60\,000$ ) spectrograph *Coralie* at the Swiss 1.2m Euler telescope located at ESO La Silla Observatory in Chile. *Coralie* is described in Queloz et al. (2001). Ségransan et al. (2010) provide a description of instrumental updates made in 2007. An efficient reduction pipeline is available for *Coralie*. The reduction follows standard procedure and performs pre- and overscan bias correction, flatfielding using Halogen lamps, and background modelization, as well as cosmic removal. ThAr lamps are used for the wavelength calibration.

RVs were determined via cross-correlation (Baranne et al. 1996; Pepe et al. 2002) using a numerical mask designed for solar-like stars (optimized for spectral type G2). The instrument is tried and tested, and is renowned for its stability and very high precision of  $\sim 3 \text{ m s}^{-1}$  (Pepe et al. 2003; Ségransan et al. 2010).

All data used here are made publicly available at the CDS<sup>1</sup>

## 3. Results

Using the new *Coralie* data, modulations in shape and amplitude of RV curves are discovered in four Cepheids of rather different natures (pulsation mode and period, mass and radius). Figure 1 shows the modulations for one of these,  $\ell$  Car. Figures for the other three targets are provided in the online appendix. Interestingly, the short-period Cepheids exhibit smooth long-term modulations, whereas the long-period Cepheids exhibit variations between subsequent pulsation cycles. More details on this and other features of the modulations will be presented in a forthcoming publication.

To estimate the impact of RV modulation on BW distances, data from two epochs are used following Eq. 3. Table 1 summarizes the observational data and results employed in this estimation, and lists the peak-to-peak RV amplitude variations between epochs ( $\Delta A_{v_r}$ ), the integrals of the RV curves ( $\Delta R/p$ ), and the relative distance error as defined in Eq. 3. To compute the integrals, the per-epoch data were represented by splines for QZ Nor,  $\ell$  Car, and RS Pup. A second-order Fourier series was more appropriate for V335 Pup. The central values and uncertainties for  $\Delta A_{v_r}$ ,  $\Delta R/p$ , and  $\text{err}(d)$  were then determined using a classical Monte Carlo method, in which the analysis was repeated 10 000 times using randomly offset datapoints (offsets drawn from a normal distribution with variance equal to the squared measurement uncertainties).

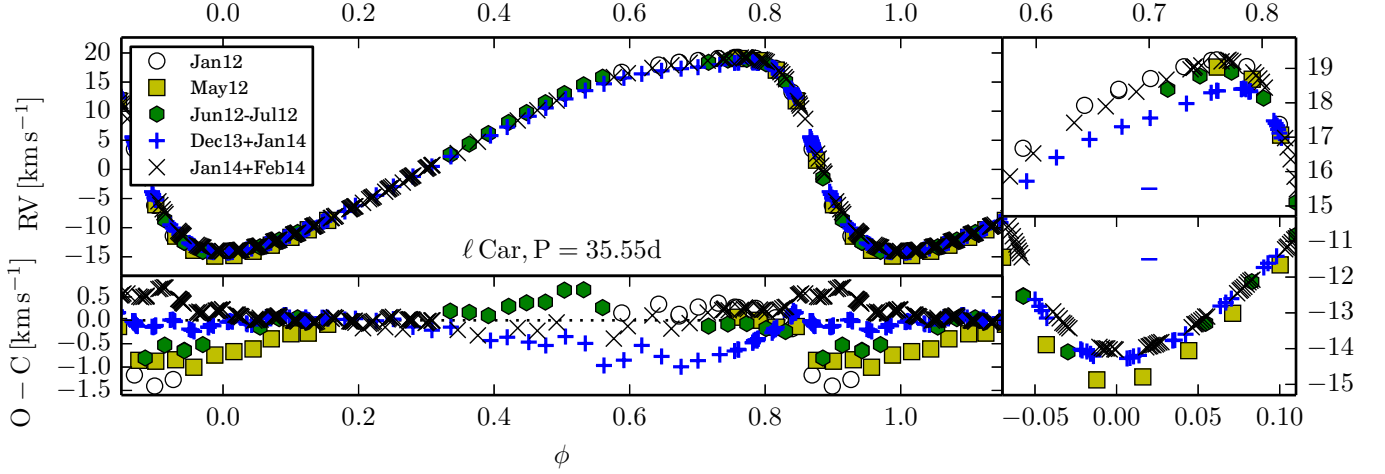
**QZ Normae** The *s*-Cepheid QZ Normae resides in the open cluster NGC 6067 (see Anderson et al. 2013, and references therein), making it an important calibrator for the Galactic PLR. Interestingly, the modulations are asymmetric around the mean and are significantly larger during contraction than during expansion. The smoothly and steadily increasing amplitude is traced closely over an observational baseline of nearly three years. Two well-traced epochs lying 2.1 years apart yield significantly different values for  $\Delta R$  (increasing with time), leading to a possible systematic distance error of nearly 15%.

**V335 Puppis** The modulations in this *s*-Cepheid smoothly decreased RV amplitude over a period of nearly three years, before a reversal became apparent in February 2014. This contrasts with the modulation in QZ Nor, which thus far has not shown a reversal. Using the two most extreme (in terms of amplitude) pulsation cycles yields  $\Delta R$  values that differ by 11%.

<sup>1</sup> <http://cds.u-strasbg.fr/>

Cepheid	HD	S/N	N <sub>1</sub>	N <sub>2</sub>	$\Delta t$ [yr]	BJD <sub>1</sub> [d]	BJD <sub>2</sub> [d]	$\Delta A_{v_r}$ [km s <sup>-1</sup> ]	$\Delta R_1/p$ [R <sub>⊙</sub> ]	$\Delta R_2/p$ [R <sub>⊙</sub> ]	err(d) [%]
QZ Nor	144972	29	18	16	2.1	5660.3	6430.3	$-1.26 \pm 0.05$	$1.10 \pm 0.01$	$1.26 \pm 0.01$	$-14.5 \pm 0.6$
V335 Pup	65227	36	11	30	2.8	5659.6	6660.8	$1.12 \pm 0.01$	$1.06 \pm 0.01$	$0.95 \pm 0.01$	$10.3 \pm 0.2$
ℓ Car	84810	257	110	151	c2c	6660.7	6701.7	$-0.51 \pm 0.06$	$22.42 \pm 0.01$	$23.62 \pm 0.01$	$-5.1 \pm 0.1$
		263	37	86	1.7	6089.5	6659.7	$1.35 \pm 0.31$	$23.95 \pm 0.02$	$22.42 \pm 0.01$	$6.8 \pm 0.1$
RS Pup	68860	133	124	170	c2c	6660.8	6703.6	$1.32 \pm 0.11$	$35.38 \pm 0.01$	$33.93 \pm 0.01$	$4.3 \pm 0.1$
		125	29	131	1.1	6327.6	6661.6	$-3.03 \pm 0.08$	$32.79 \pm 0.12$	$35.42 \pm 0.01$	$-7.4 \pm 0.4$

**Table 1.** Estimating the possible impact of modulations on BW distances using RV data from different epochs. The columns list: median signal-to-noise ratio (S/N) of the spectra at 5700Å; number of observations per epoch (N<sub>1,2</sub>); baseline ( $\Delta t$ ) between the epochs considered (c2c indicates two consecutive pulsation cycles); median Barycentric Julian dates, less 2 450 000 (BJD<sub>1,2</sub>).  $\Delta A_{v_r}$  is the change in peak-to-peak RV amplitude due to modulation. Columns  $\Delta R_{1,2}/p$  list the per-epoch RV curve integrals, cf. Eq. 2. The last column (err(d)) quantifies the systematic uncertainty on BW distances due to modulation if non-contemporaneous  $\Delta R$  and  $\Delta \Theta$  are used to determine the distance, cf. Eq. 3.



**Fig. 1.** New *Coralie* RV data for  $\ell$  Car. The large panel shows the phased RV curve, distinguishing data from different epochs by symbol style and color. The two right-hand panels provide close-ups around maximum (upper) and minimum RV (lower), and show the median RV uncertainty as an errorbar (too small to discern in this case). The bottom panel shows residuals around an “average” Fourier series model fit to the combined data set (fit procedure described in Anderson et al. 2013). Figures for the other Cepheids are provided in the online version.

**ℓ Carinae** The long-period Cepheid  $\ell$  Carinae (HIP 47854) is particularly important for the distance scale. Firstly, the frequently adopted Galactic PLR calibration by Benedict et al. (2007) relies heavily on this star, since it is the only long-period ( $P > 10$ d) Cepheid in their sample. Secondly,  $\ell$  Car’s pulsations can be resolved by the VLTI (Kervella et al. 2004c), which enables an important cross-check of its distance via the interferometric BW method.

Significant modulations exceeding  $1 \text{ km s}^{-1}$  are evident in the data, cf. Fig. 1, where  $\ell$  Car exhibits modulations on short timescales (cycle-to-cycle), as demonstrated by observations taken between December 2013 and February 2014. These modulations can vary  $\Delta R/p$  between subsequent cycles by up to 5%. Modulations on longer timescales can be even larger, see the second row for  $\ell$  Car in Table 1. Therefore, modulations in  $\ell$  Car seem to be present on all time scales, setting a stringent constraint to observe linear and angular variations during the same pulsation cycle.

**RS Puppis** The long-period Cepheid RS Pup is a particularly interesting object due to its location in a large reflection nebula (Westerlund 1961; Kervella et al. 2008, 2012; Feast 2008) and erratic period changes (Berdnikov et al. 2009) that are also clearly seen in the present data. As the *Coralie* data shows, using non-contemporaneously determined  $\Delta R$  and  $\Delta \Theta$  can lead to systematic errors of up to 7% for its BW distance. Similar to  $\ell$  Car, significant modulations occur even between subsequent

cycles. This remarkable object requires a detailed discussion that is beyond the scope of this letter.

#### 4. Discussion

For the time being, no firm conclusions can be drawn regarding the origin of the modulations. Given that the modulation time scales are very different for the short (steady over years) and long-period Cepheids (cycle-to-cycle), it seems likely that different mechanisms are at work. A longer time baseline is required for firmer conclusions.

For the short-period Cepheids, it is tempting to speculate about the presence of a Blažko (1907) effect, which is known in RR Lyrae stars; see also the “Blazhko Cepheids” mentioned by Soszynski et al. (2008). It will be interesting to compare the properties of Cepheids exhibiting modulated RV curves with Blazhko RR Lyrae stars. Another explanation could be secular radius variations; however, V335 Pup exhibits a reversal of the modulation, which may point to a recurrent phenomenon. Another possibility are non-radial pulsations that may manifest themselves as cycle-to-cycle variations in RVs (Kovtyukh et al. 2003; Nardetto et al. 2014). Strange pulsation modes (Buchler et al. 1997; Buchler & Kolláth 2001) could also provide an explanation, since the predicted amplitudes are similar to the observed modulations.

One exciting possibility for the long-period Cepheids could be that their modulations reveal the coupling between convec-

tion and pulsations. This is plausible, given that these Cepheids are cooler and have very deep convective envelopes. If this is the case, then  $\ell$  Car and RS Pup provide important constraints for the modelization of the cool edge of the instability strip and hydrodynamical models (e.g., Mundprecht et al. 2013).

Another possible explanation of the cycle-to-cycle nature could be variations in the observed stellar disk due to surface inhomogeneities (spots) moving in and out of the field of view. If spots are sufficiently long-lived, a long-term (quasi-)periodicity of the modulation might indicate such an effect. However, short-period Cepheids have rotation periods on the order of five months (assuming  $30 R_{\odot}$  and equatorial velocity  $10 \text{ km s}^{-1}$ ), which is shorter than the observed modulation timescale (several years). Conversely, long-period Cepheids exhibit shorter modulation timescales (cycle-to-cycle), while their rotation periods are significantly longer (years) due to large radii. Since rotation has important evolutionary effects on Cepheids (Anderson et al. 2014), it would be particularly useful to obtain additional information about rotation periods and velocities.

Cepheids have highly complex atmospheres and exhibit strong velocity gradients (e.g., Dawe 1969; Butler 1993; Nardetto et al. 2006). Since the RVs determined here are derived from a chosen set of spectral lines, it is possible that the RV modulations point towards long-term variations in the time-dependent velocity structure of Cepheid atmospheres. Further investigation in this direction is currently in progress.

It is currently unclear whether RV modulations are mirrored by modulations in  $\Delta\Theta$ . To search for such signs using surface brightness methods, a long-term photometric precision of  $\sim 10 \text{ mmag}$  in both V and K-band is required. Evans et al. (2014) have recently reported on “flickering” in space-based photometric observations of RT Aurigae at the level of  $20 - 40 \text{ mmag}$ . The interferometric precision achieved for  $\ell$  Car (Kervella et al. 2004c) may be sufficient to detect this modulation directly using multi-epoch VLTI observations. A systematic search for modulations using photometry and interferometry is thus indicated to better understand the phenomenon and mitigate its impact on the BW technique.

## 5. Conclusions

This *letter* presents newly discovered modulations in the radial velocity curves of four classical Cepheids. The modulations reveal additional complexity in the pulsation of these fundamental distance tracers. The four Cepheids exhibiting modulations have very different natures, two with short and two with long periods. This fact is suggestive of a) the phenomenon being common among Cepheids and/or b) different mechanisms being at work (different time scales for long and short-period Cepheids).

Modulations can create significant systematic uncertainty for BW distances, if non-contemporaneous data are employed. If RV modulations are mirrored by photospheric radius variations, they should be detectable using high-precision photometry or interferometry. Such observations are required to better understand the phenomenon and to establish ways of mitigating its impact on BW distances. Furthermore, only contemporaneous linear and angular radius variations should be used in BW analyses. Short-period Cepheids should be observed over up to a few weeks duration to ensure good phase coverage from a single observatory. For long-period Cepheids, excellent phase coverage must be obtained during individual pulsation cycles.

Several possible effects explaining the phenomenon can be found in the literature. However, a longer observational baseline is required to further investigate the origin of modulations.

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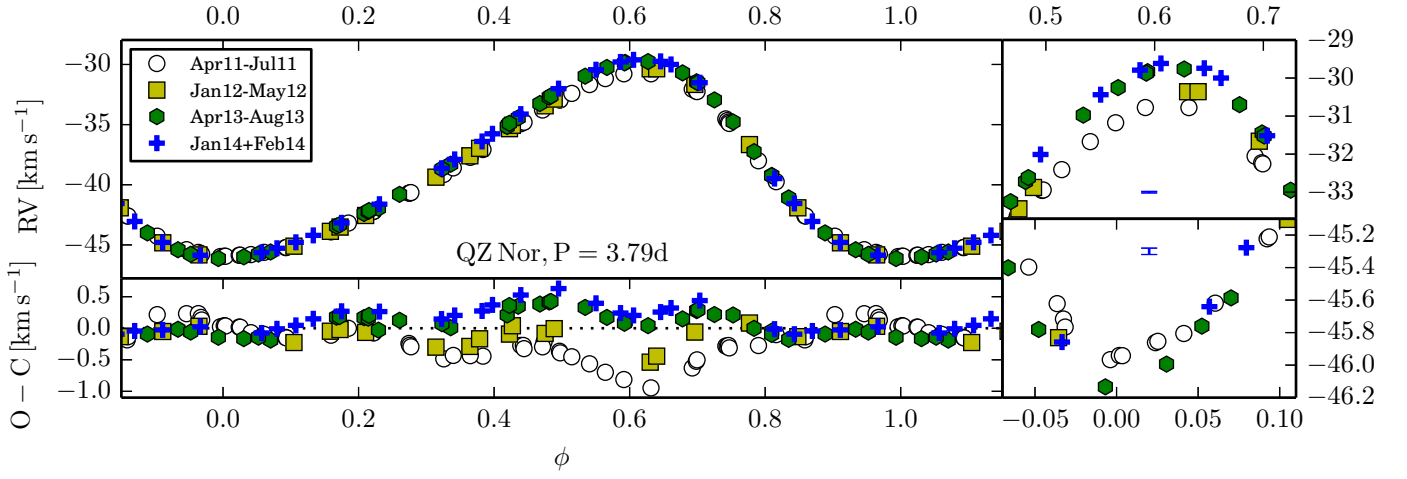
## List of Objects

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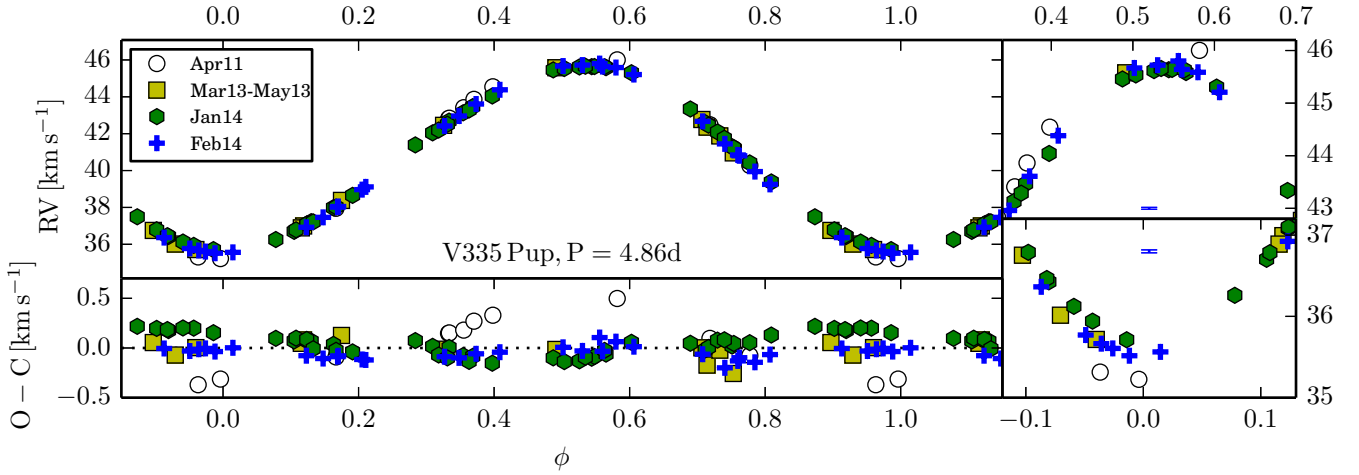
## Appendix A: Supporting figures

This appendix contains Figs. A.1, A.2, and A.3 that are analogous to Fig. 1. These figures unambiguously show the modulations discovered. The full dataset employed to create these figures will be made publicly available through the CDS.

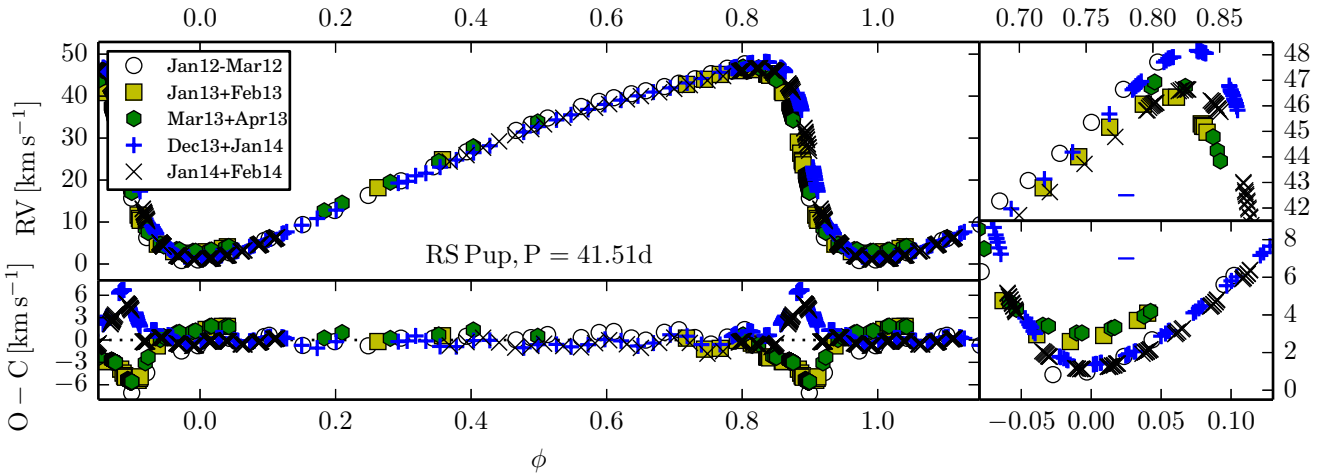
Finally, Fig. A.4 shows the residuals of the models fit to the per-epoch data used to estimate the impact of modulation as a systematic uncertainty for Baade-Wesselink distances as listed in Table 1. The data were modeled as cubic splines for QZ Nor,  $\ell$  Car, and RS Pup, and as a second-order Fourier series for the *s*-Cepheid V335 Pup.



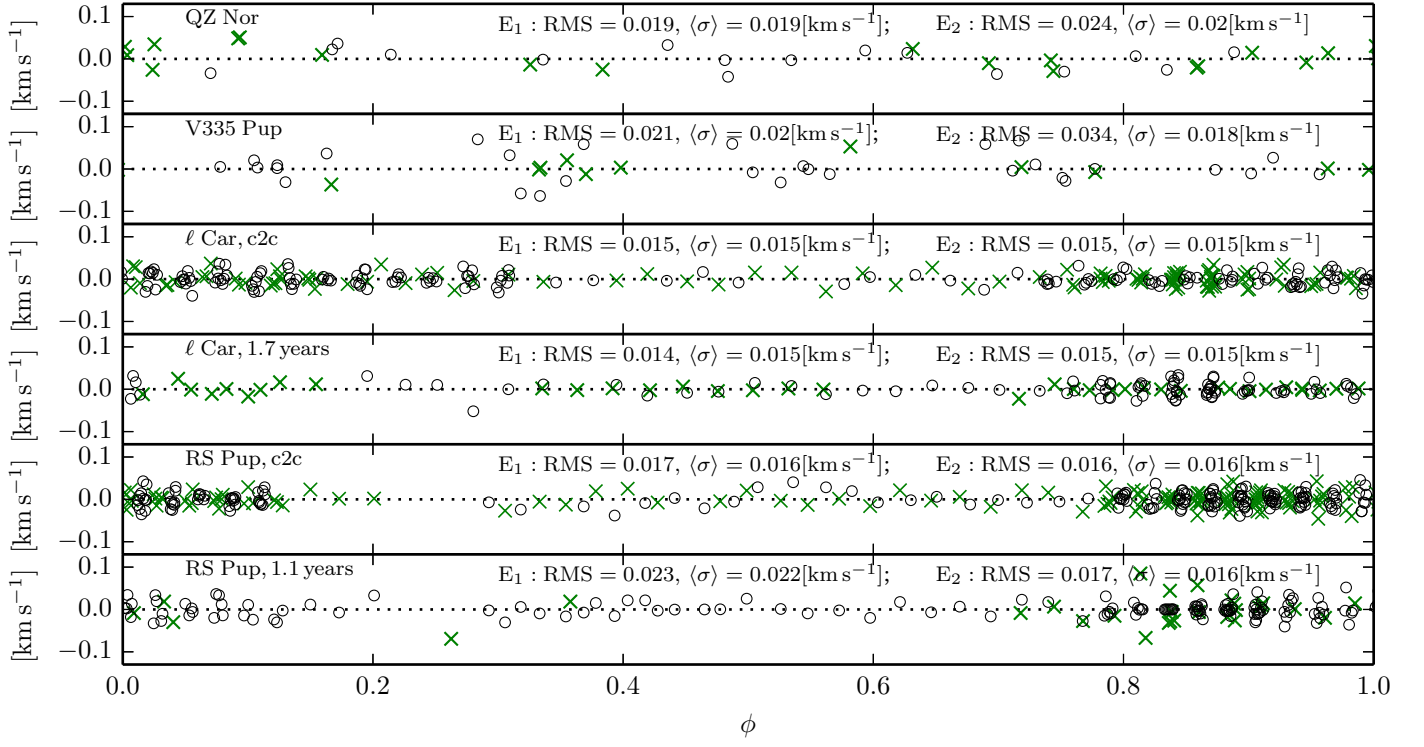
**Fig. A.1.** New *Coralie* RV data for QZ Nor. The large panel shows the phased RV curve, distinguishing data from different epochs by symbol style and color. The two right-hand panels provide close-ups around maximum (upper) and minimum RV (lower), and show the median RV uncertainty as a blue errorbar. The bottom panel shows residuals around an “average” Fourier series model fit to the combined data set (fit procedure described in Anderson et al. 2013).



**Fig. A.2.** Analogous to Fig. A.1 using RV data for V335 Puppis.



**Fig. A.3.** Analogous to Fig. A.1 using RV data for RS Puppis. RS Puppis also exhibits significant random cycle-to-cycle fluctuations in pulsation period (Berdnikov et al. 2009). As the close-up panels demonstrate, these random period fluctuations occur *in addition* to the modulation of the RV amplitude.



**Fig. A.4.** Fit residuals from the epochs (E<sub>1</sub> and E<sub>2</sub>) used to estimate the impact on BW distances for all four Cepheids as listed in Table 1. For  $\ell$  Car and RS Pup, both the cycle-to-cycle and longer timescales are shown. The earlier epoch is represented by green x markers, the later epoch by black open circles. For each epoch, the RMS around the fit and median measurement uncertainty,  $\langle \sigma \rangle$ , are printed in the corresponding panel, indicating excellent fits.